A Plasma Model of Quasars and Radio Galaxies

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P. A. Sturrock

Lectures Presented at International School of Physics "Enrico Fermi"
29th Course, Plasma Astrophysics, Varenna, Italy, July 1966

Reporter: P. A. Feldman

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PREFACE

Since this is a school of plasma-astrophysics, it seems particularly appropriate for us here to deal with the phenomena associated with quasi-stellar objects (quasars) as plasma phenomena and to see how much progress can be made. Admittedly, this will at best be a partial treatment of the problem, since it will omit atomic and nuclear processes; but it does seem to offer the best hope of understanding the observations of high-energy radiation, and it does lead to a model of what these objects are and how they form, which can then be studied from other points of view.

LECTURES PRESENTED AT INTERNATIONAL SCHOOL OF PHYSICS "ENRICO FERMI"

A. Although the nature of quasars[1,2,3] remains an open question, it seems that there are a number of similarities between the quasi-stellar radio sources and conventional radio galaxies.

1. The radio clouds produced by both types of object have similar spectra. (However, the "point" radio source of a quasar typically shows a flatter spectrum with low-frequency cut-off.)
2. Double structure is characteristic of radio clouds of both types of objects.
3. At least one radio galaxy (NGC 1275) displays one of the most striking characteristics of quasars, that of radio variations.[4]
4. One quasar, the nearest one (3C273), shows a very clear jet (visible most likely by optical synchrotron radiation); at least one radio galaxy (M87) shows a similar jet.
5. The classification of radio sources by Matthews, Morgan and Schmidt[5] shows that the sequence of increasing luminosity is also a morphological sequence, in the course of which the nucleus becomes smaller and more brilliant. Quasars are at the end of this sequence.

The explosions of quasars and the explosions in certain galaxies that are strong radio emitters are probably quite similar. In both cases a great quantity of energy is suddenly released as relativistic charged particles, the kinetic energy of ejected gas clouds, and possibly other forms. It is generally believed that the observed radio emission is produced by the interaction of high-energy electrons with magnetic fields. However, since no theory has been developed that accounts for the explosions in strongly-emitting, conventional radio galaxies, it is not possible to understand quasars by direct analogy with their (apparently) closest "relatives."

Apart from geophysical phenomena and similar events on Jupiter, only two other explosive astrophysical events, supernovae and solar flares, are known to generate high-energy particles and thereby produce nonthermal radio emission. Both phenomena should be considered for their possible applicability to an explanation of the properties of quasi-stellar sources and radio galaxies.

There are a number of considerations that argue against identifying explosions in quasars with supernova-like explosions. For example, supernova explosions are expected to be spherically symmetrical rather than highly asymmetric. Supernova explosions are expected to release a fairly well defined amount of energy, whereas explosions in radio galaxies or quasars release amounts of energy covering a very wide range of magnitude. (Minor "flares" or "flashes" in quasars release comparatively small amounts of energy.)

Some attention has been given to the possibility that a statistical occurrence of supernovae in a massive, highly compact galaxy might account for the puzzling, short-period time variations exhibited by a number of quasars,[6] but no model of this sort can account for the major explosions of quasars. Even if a good case could be constructed for the applicability of the supernova mechanism to the problem of quasi-stellar explosions, one could hope to obtain only the barest phenomenological understanding of quasars by employing the current, rudimentary theories of supernovae. Clearly, one is not going to get very far with this approach.

On comparing the properties of solar flares with the observations of galactic and quasar explosions, we were personally impressed by the striking similarities on a number of key points. We do not want to go through these comparisons in detail at this stage of our discussion, but two points in particular are worth mentioning now.

1. Both flares and quasar explosions show a directive nature. The sharpest directionality yet observed in quasars is the jet of 3C 273. Something like this is known to occur on the sun: the Type II radio bursts[7] that are produced in association with flares arise from similarly narrow jets of plasma.
2. Both flares and quasars appear to convert relatively large fractions of their available energy into high-energy particles, which subsequently give rise to electromagnetic radiation.

This is a most important consideration, to which Prof. G. R. Burbidge has referred to in his lectures,[8] stressing the surprisingly high apparent efficiency of "galactic accelerators" compared with man-made accelerators. It is our view that the significance of this comparison is that astrophysical accelerators are much simpler in construction than man-made accelerators. If a machine is to have a low efficiency, there must be parts which can dissipate energy in competition with the particles which are being accelerated. If a machine is so simple that no such parts exist, the efficiency must be high.

B. We now proceed on the assumption that the principal properties of quasars can be understood fairly directly as plasma phenomena. Super-efficient nuclear processes, gravitational collapse, anti-matter annihilation, and other exotic energy production mechanisms will not be invoked.

The principal difficulty in discussing the problem in this context is that of understanding the structure and strength of the magnetic field that is associated with quasars. Later, the origin and the possible effects of the field can be considered quite naturally. Although direct and detailed observations of the magnetic field are not available, we believe that certain sensible statements can already be made.

1. 3C 47 and a number of other quasars have a double radio-cloud structure[2] (see Fig. 1).
2. It is believed that a magnetic field is present in the clouds since the radio emission that is detected seems to be produced by the synchrotron mechanism.
3. In general, the configuration of this magnetic field can be characterized as either "closed" or "open." The former assumption leads to theoretical difficulties, especially with regard to energetics.

Namely, there is a magnetic-energy problem in the sense that the energy of the magnetic field ($W_M \propto R^{-1}$) must once have been much greater than "at present" since the field-containing region probably expanded by a factor of at least 100, and possibly much more, in attaining its "present" size. Also, there is an electron-deceleration problem in the sense that a 100 to 1 transverse expansion of the magnetic field would have resulted in a reduction of the energy of the radiating particles ($E \propto R^{-1}$) by a factor of 100. Thus, much higher particle energies would be required at the time of the original explosion than at the time of the radio emission that is currently observed. It does not help very much to assume that the magnetic field is closed but tied to the nucleus; much the same energy difficulties remain.

The magnetic field in the radio cloud must then be <u>open</u> and attached in some way to the intergalactic field. Accordingly, it must be a <u>primeval</u> field. (An alternative explanation of the origin of the magnetic field in terms of some dynamo process seems unlikely in the case of very massive stars or galaxies. It would seem that the most sensible assumption under the circumstances, including our present lack of knowledge

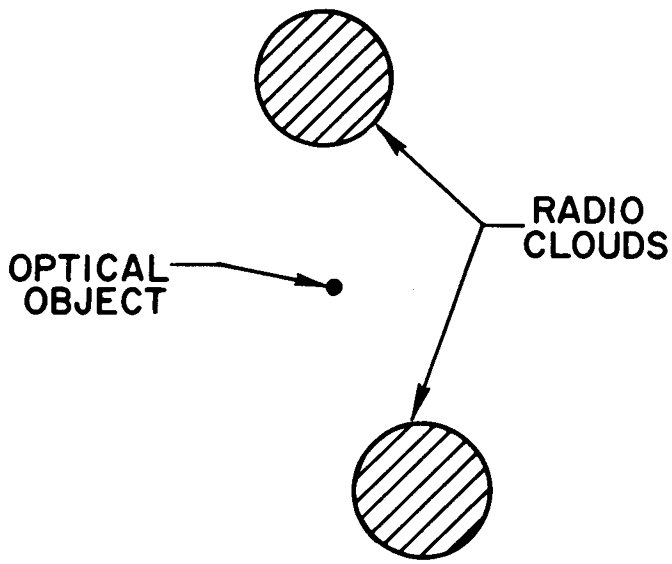

FIG. 1. TYPICAL DOUBLE STRUCTURE OF RADIO SOURCES.

about dynamo mechanisms, is that the magnetic field of quasi-stellar objects is of primeval origin.)

If the magnetic field in the radio cloud(s) is open, either it is coupled to the nucleus or it is not. The latter possibility leads to formidable difficulties; for instance, how would high-energy particles and other ejected matter get from the massive nucleus (where the energy resides) to the position of the radio cloud? Charged particles and highly conducting plasma cannot very well travel across field lines. Hence, we are led to consider a magnetic field that is open, of primeval origin, and coupled to the "galaxoid" (see Fig. 2 below). The term "galaxoid" will be used indiscriminately for a galactic nucleus or an optical quasi-stellar object. This is only a rough picture that will be modified and refined as we continue the discussion.

C. If the cosmological interpretation of the large red shifts of quasi-stellar sources is accepted (and it seems to pose more problems than it solves to adopt the "local" hypothesis), the problem of energetics immediately comes to the fore. Whether the energy output is derived from gravitational or nuclear processes, masses of the order of $10^8 M_\odot$ or larger are necessary to explain the observed radiation fluxes. Despite these huge masses the observed light variations require the optical objects to be quite small, of the order of a light week or less.

It is not surprising, therefore, that many early theoretical attempts to understand the nature of these objects concentrated on the behavior of super-massive stars! Instabilities were sought that would release energy in both the right amount and the proper forms. It was found that massive gas- and radiation-supported bodies are characterized by a γ that is very close to 4/3. If the polytrope index is less than 4/3, the object is unstable. Relativistic effects have the effect of reducing the polytrope index so that instabilities of relativistic origin occur.[9] However, the resulting energy output[10] is insufficient to explain the amount of energy released in a large quasar explosion. Moreover, there is no provision in these models to explain the <u>forms</u> of the energy release, such as highly accelerated particles. In order to deal with the electromagnetic phenomena (acceleration and radiation) associated with quasars, Maxwell's

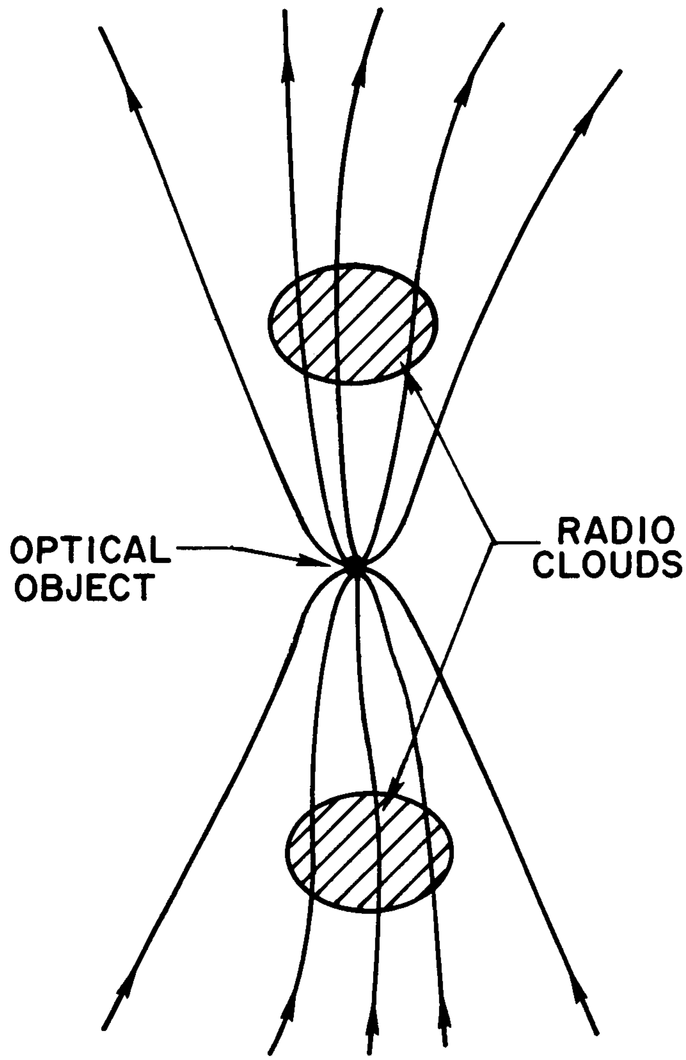

FIG. 2. OPEN TOPOLOGY OF MAGNETIC FIELD AND ITS CONNECTION TO OPTICAL OBJECT.

equations must enter the calculations. If this statement is accepted, it follows that any theory of quasars which does not involve Maxwell's equations must be wrong.

Let us examine the consequences of assuming that the massive optical nuclei of quasars are supported by magnetic stresses in addition to gas and radiation pressure. The strength of the field inside the central object can be estimated from the flux derived from radio observations of the associated radio cloud(s). One finds from the compilation by Maltby, Matthews and Schmidt[11] of the estimated dimensions and magnetic field strengths of a number of strong galactic radio sources that the magnetic flux threading a radio cloud is typically of order 10^{41} gauss cm^2. If this entire flux threads an object of the dimensions of one light month ($\sim 10^{17}$ cm), the magnetic field inside would be of the order of 10^7 gauss. Although this value may be too high because of uncertainties in the appropriate parameters for the radio cloud, it is difficult to avoid the conclusion that fields of the order of a million gauss are present inside the nucleus, and that magnetic stresses are by no means negligible in determining the structure of these objects.

A simplified first approach might be to consider a static model in which the magnetic stresses are primarily responsible for balancing the self-gravitational attraction of the mass and preventing its collapse. This is consistent with the idea that a flare-like mechanism is operative in quasars since the energy released by this mechanism is likely to be mostly magnetic in origin. The gravitational binding energy W_{GB} of a roughly spherical object of fixed mass and varying characteristic dimension R varies as R^{-1}. The magnetic energy W_M associated with a field of given shape but varying scale varies as R^{-1} since $B \propto R^{-2}$ if the magnetic flux is fixed. Since both W_{GB} and W_M vary as $1/R$, the magnetic field is capable of providing neither stability nor instability, only gross neutral stability, in this nonrelativistic treatment. Moreover, the assumption that the magnetic field is primarily responsible for counteracting gravitational self-attraction is unattractive since plasma would then tend to collect in a minimum energy state determined by the magnetic field configuration, as indicated schematically in Fig. 3.

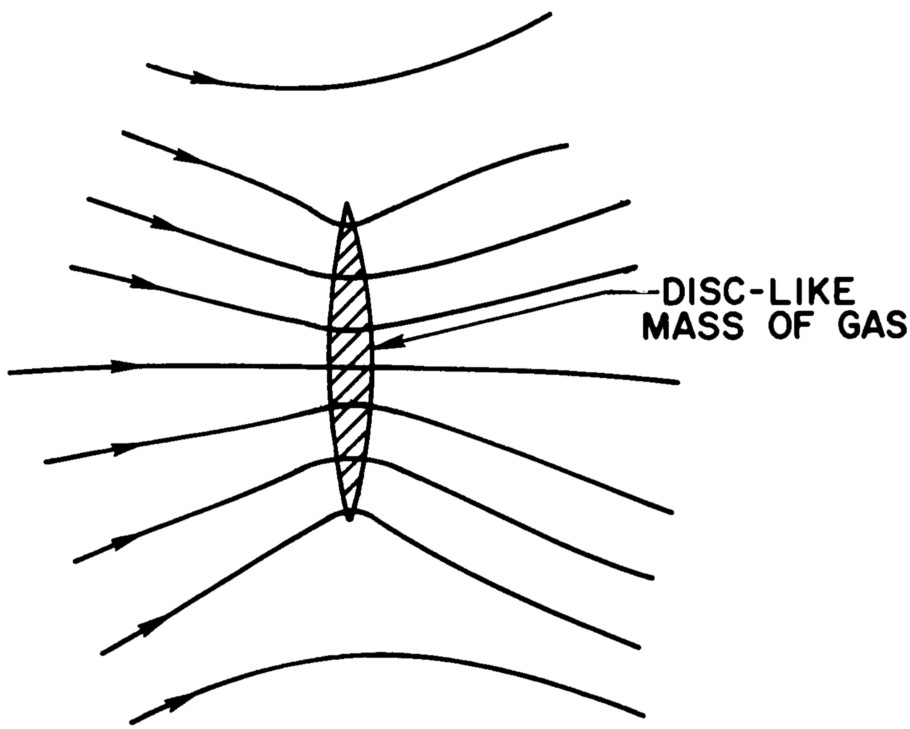

FIG. 3. STRUCTURE OF OBJECT IN THE CASE THAT PRESSURE IS NEGLIGIBLE.

We want to be able to deal with a wider variety of forms than this restriction would seem to allow. Also, there is the theoretical difficulty that this minimum energy state is one in which the density either vanishes or diverges at each point. This situation arises because gas can flow freely along field lines and will collect at the point or points of lowest gravitational potential on each field line. Clearly, while the gravitational force normal to the field lines may be balanced primarily by magnetic stresses, some other force must be responsible for preventing gravitational collapse along the field lines. If this role is assigned to ordinary gas pressure, temperatures of the order of 10^9 °K are needed. Again, we would be faced with the structure and stability problems of radiation-supported, super-massive objects. These we are most anxious to avoid.

D. The observed optical and radio fluctuations indicate that quasars are nonstatic; the influence of plasma turbulence on the stability properties should therefore be considered.

The effective value of γ for hydromagnetic turbulence in the presence of a strong magnetic field can be obtained by a simple argument. In this case the plasma motion may be analyzed into a superposition of hydromagnetic waves with phase velocities determined by the Alfvén speed

$$v_A = \frac{B}{(4\pi\rho)^{1/2}} . \tag{1}$$

Now, consider a system with a time-varying characteristic dimension R that changes slowly in comparison with the wave frequencies. Then the energy of each mode will vary as the wave frequency according to the adiabatic theorem. The dispersion relation for the MHD modes is

$$\omega^2 = v_A^2 k^2 \tag{2}$$

if the gas temperature is low enough for the Alfvén speed to be much greater than the speed of sound. Therefore, as the scale changes slowly, the energy of each mode E_w varies as

$$E_w \propto \omega \propto v_A k \ . \tag{3}$$

Clearly, the wave numbers will change inversely with the scale, i.e.,

$$k \propto R^{-1} \ . \tag{4}$$

Therefore

$$E_w \propto \frac{B}{\rho^{1/2}} R^{-1} \ . \tag{5}$$

If the system is confined to a "box" so that the magnetic flux Φ and the mass M are constants during the change of scale,

$$B \propto \frac{\Phi}{R^2} \propto R^{-2} \tag{6}$$

and

$$\rho \propto \frac{M}{R^3} \propto R^{-3} \ . \tag{7}$$

Therefore,

$$E_w \propto R^{-3/2} \tag{8}$$

for any wave number k.

Since the energies (and the frequencies) of all the modes will change in the same proportion, the total energy E_T of the waves will also change in that proportion:

$$E_T \propto R^{-3/2} \ . \tag{9}$$

The effective pressure p_T of the hydromagnetic turbulence will be a multiple of the energy density of the turbulence. Therefore,

$$p_T \propto \frac{E_T}{R^3} \propto R^{-9/2} \ . \tag{10}$$

Using Eq. (7), we find that

$$p_T \propto \rho^{3/2} , \tag{11}$$

indicating that

$$\gamma = 3/2 . \tag{12}$$

Since $3/2 > 4/3$, it would appear that MHD turbulence can exert a stabilizing influence.

E. Now we can proceed to investigate the equilibrium state and the stability of the nucleus. Instead of beginning with a virial theorem, we follow an equivalent procedure using the principle of virtual work.

The total energy W_0 is given approximately by

$$W_0 = W_K + W_T + W_M - W_{GB} + W_{MR} - W_{GBR} . \tag{13}$$

where W_K is the kinetic energy of large-scale mass motions (such as radial pulsations); W_T is the total energy of MHD turbulence; W_M is the magnetic energy associated with the large-scale field; and W_{GB} is the gravitational binding energy. W_{MR} and W_{GBR} are the post-Newtonian relativistic corrections[12] to the magnetic energy and the gravitational binding energy, respectively. Only these corrections need be included if W_M and W_{GB} are the dominant contributions to the total energy. The effect of rotation is assumed to be negligible.

Consider the special case of radial pulsations of a spherically symmetric mass. The non-relativistic quantities W_K, W_M, and W_{GB} are given by

$$W_K = \frac{1}{2} \int \rho \, v_r^2 \, dV \tag{14}$$

$$W_M = \frac{1}{8\pi} \int B^2 \, dV \tag{15}$$

and

$$W_{GB} = \int \frac{GM_r}{r} \rho \, dV \ , \tag{16}$$

where v_r is the macroscopic radial velocity of the pulsations and M_r is the mass within a sphere of radius r. One finds from the formulas given by Fowler[12] that the post-Newtonian corrections W_{MR} and W_{GBR} are given by

$$W_{MR} = \frac{1}{8\pi} \int \frac{GM_r}{c^2 r} B^2 \, dV \tag{17}$$

and

$$W_{GBR} = \int \frac{3}{2} \frac{G^2 M_r^2}{c^2 r^2} \rho \, dV \ . \tag{18}$$

Note that the integrands in Eqs. (17) and (18) differ from the integrands in Eqs. (15) and (16), respectively, by a factor of the order of

$$\frac{2GM_r}{c^2 r} = \frac{R_{s,r}}{r} \ ,$$

where $R_{s,r}$ is the Schwarzschild radius corresponding to the mass M_r.

A necessary condition for equilibrium may be obtained by using the principle of virtual work as follows: assume that, for some configuration, $W_K = 0$ and then require that a first-order change of the configuration does not result in a first-order change in W_K. If the change of configuration is simply a change of scale that preserves the spherical symmetry, the magnetic flux, and the mass, it is clear from Eqs. (15) through (18) that

$$W_M \propto R^{-1}, \quad W_{GB} \propto R^{-1}, \quad W_{MR} \propto R^{-2}, \quad W_{GBR} \propto R^{-2} \ . \tag{19}$$

The scale dependence of W_T is given by Eq. (9):

$$W_T \propto R^{-3/2} \ .$$

Now consider a small change of scale

$$R \rightarrow (1 - \epsilon) R \ . \tag{20}$$

The various contributions to the total energy of the configuration are then the following:

$$\left.\begin{aligned}
W_M &\rightarrow (1-\epsilon)^{-1} W_M \cong (1+\epsilon) W_M \\
W_{GB} &\rightarrow (1-\epsilon)^{-1} W_{GB} \cong (1+\epsilon) W_{GB} \\
W_{MR} &\rightarrow (1-\epsilon)^{-2} W_{MR} \cong (1+2\epsilon) W_{MR} \\
W_{GBR} &\rightarrow (1-\epsilon)^{-2} W_{GBR} \cong (1+2\epsilon) W_{GBR} \\
W_T &\rightarrow (1-\epsilon)^{-3/2} W_T \cong \left(1+\frac{3}{2}\epsilon\right) W_T ,
\end{aligned}\right\} \tag{21}$$

where only first-order terms in ϵ have been retained. Applying the principle of virtual work, we obtain the equilibrium condition

$$\frac{3}{2} W_T + W_M - W_{GM} + 2W_{MR} - 2W_{GBR} = 0 . \tag{22}$$

In order to discuss stability, however, it is necessary to work to second order in the small quantity ϵ. Since we wish to deal with radial pulsations, ϵ must be allowed to be time dependent. The total energy W_0 can then be expressed in terms of an expansion in powers of ϵ (and $\dot{\epsilon}$) as follows:

$$W_0 \rightarrow W_0 + \epsilon W_1 + \frac{1}{2}\epsilon^2 W_2 + \frac{1}{2} I\dot{\epsilon}^2 + \ldots \tag{23}$$

W_1 is just the left-hand side of Eq. (22):

$$W_1 \equiv \frac{3}{2} W_T + W_M - W_{GM} + 2W_{MR} - 2W_{GBR} , \tag{24}$$

which is zero if the state $\epsilon = 0$ is an equilibrium state, and W_2 is given by

$$W_2 = \frac{3}{4} W_T + 2W_{MR} - 2W_{GBR} , \tag{25}$$

where use has been made of the equilibrium condition in Eq. (22). The last term in Eq. (23) is the second-order contribution from W_K, i.e.,

$$W_K \rightarrow \frac{1}{2} I\dot{\epsilon}^2 , \tag{26}$$

where

$$I \equiv \int \rho r^2 \, dV . \tag{27}$$

Before taking up the question of stability, let us examine the equilibrium state (assuming that one does, in fact, exist). Since W_M and W_{GB} are taken to be much larger than the other contributions to the first-order energy term, Eq. (22) yields the approximate relation

$$W_M \approx W_{GB} . \tag{28}$$

This is a very interesting result, as we shall see.

Consider, for example, the simple model of a sphere of radius R and mass M with uniform density ρ. The internal magnetic field B is taken to be uniform, while the external field is (for simplicity) assumed to have a current-free dipolar configuration. In this case

$$W_M = \underbrace{\frac{1}{6} R^3B^2}_{\text{inside}} + \underbrace{\frac{1}{12} R^3B^2}_{\text{outside}} = \frac{1}{4} R^3B^2 \tag{29}$$

and

$$W_{GB} = \frac{3}{5} GM^2R^{-1} . \tag{30}$$

Equation (28) provides an approximate relation between the three quantities M, R, and B. If M and R are regarded as the independent parameters by which the model is to be characterized,

$$B = \left(\frac{12}{5} G\right)^{1/2} MR^{-2} . \tag{31}$$

This enables us to relate Φ, the total magnetic flux that threads the spherical nucleus, with the mass M, provided that the object is supported against collapse principally by magnetic stresses. Namely,

$$\Phi = \pi BR^2 = \pi\left(\frac{12}{5}G\right)^{1/2} M . \tag{32}$$

Numerically, this is approximately

$$\Phi \approx 10^{-3} M . \tag{33}$$

If the mass is supported against gravity by forces other than magnetic forces, the mass may be larger than that indicated by Eq. (33), leading us to the inequality

$$M \geq 10^3 \Phi . \tag{34}$$

Adopting assumptions originally proposed by Burbidge,[13] Maltby, Matthews and Moffet[11] estimate parameters for the radio clouds of a number of strong radio sources. From their tabulation of the volume and magnetic-field strength, we can easily derive an estimate of magnetic flux:

$$\Phi \approx B\, V^{2/3} . \tag{35}$$

If we ignore the components associated with the "core" or "nucleus" of a galaxy, the remaining components have magnetic fluxes in the range of $10^{40.4}$ to $10^{42.7}$ gauss cm^2. The lower limits of the masses of the associated objects are found from Eq. (34) to be in the range $10^{43.4}$ to $10^{45.7}$ gm, i.e., $10^{10.1}$ to $10^{12.4}$ $M_\odot$. The assumptions underlying these calculations[13] are open to question, so that the above mass estimates should be accorded a corresponding flexibility. With this provision in mind, it seems fair to state that Eq. (34), derived from our assumptions about the topology of the magnetic field associated with a strong radio source, is compatible with the idea that the magnetic flux threading the radio cloud of a radio galaxy also threads the parent galaxy, or the nucleus of the parent galaxy. This quantitative check on Eq. (34) should encourage us to pursue our intention of applying the same ideas to quasi-stellar radio sources.

Let us return to the question of the stability of the equilibrium in our model. We see that since the total energy W_0 is constant, the two second-order contributions to it, $\frac{1}{2}\epsilon^2 W_2$ and $\frac{1}{2} I\dot{\epsilon}^2$, are compatible only if ϵ varies appropriately with time. For instance, consider the normal mode

$$\epsilon = \epsilon_o \sin \omega t \ . \tag{36}$$

The sum $\frac{1}{2}\epsilon^2 W_2 + \frac{1}{2} I\dot{\epsilon}^2$ must be a constant for the total energy to be conserved during the radial oscillations, i.e.,

$$\frac{1}{2}\epsilon_o^2 \sin^2\omega t \ W_2 + \frac{1}{2} I\dot{\epsilon}_o^2\omega^2 \cos^2 \omega t = \text{constant} \ .$$

Therefore

$$\omega^2 = \frac{W_2}{I} = \frac{1}{I}\left(\frac{3}{8} W_T + W_{MR} - W_{GBR}\right) \ . \tag{37}$$

The stability condition is then given by

$$\omega^2 > 0 \ ,$$

or

$$\frac{3}{8} W_T + W_{MR} - W_{GBR} > 0 \ . \tag{38}$$

Even without hydromagnetic turbulence, it would appear that stability is possible if $W_{MR} > W_{GBR}$. Only quantitative calculations for a variety of configurations can resolve this question of whether this type of stabilization can actually occur.

Again let us consider the simple model of a spherical nucleus (mass M, radius R) of uniform mass density ρ. We assume that this sphere is permeated by a uniform magnetic field which changes to a current-free dipolar configuration outside. From Eqs. (17) and (18), the post-Newtonian energy terms are then

$$W_{MR} = \frac{13}{80} \frac{G}{c^2} MB^2R^2 \tag{39}$$

and

$$W_{GBR} = \frac{9}{14} \frac{G^2}{c^2} M^3R^{-2} \ . \tag{40}$$

The total turbulent energy W_T, composed of equal amounts of kinetic and magnetic wave energy, may be written as

$$W_T = \frac{1}{2} Mv_A^2 A^2 \ , \tag{41}$$

where A is the Alfvén number of the turbulence (analogous to the Mach number), defined by

$$A \equiv \frac{v_{max}}{v_A} \cong \frac{(\delta B)_{max}}{B} \ . \tag{42}$$

v_{max} is the maximum gas velocity, and $(\delta B)_{max}$ is the maximum amplitude of the magnetic field fluctuations. Using Eqs. (30) and (31), we find that W_T may be written as

$$W_T = \frac{2}{3} A^2 W_{GB} \ . \tag{43}$$

Also, from its definition in Eq. (27),

$$I = \frac{3}{5} MR^2 \ . \tag{44}$$

Therefore, upon substitution from Eqs. (39), (40), (43) and (44), Eq. (37) for ω^2 becomes

$$\omega^2 = \frac{2\pi}{3} G\rho \left(A^2 - \frac{59}{70} \frac{R_s}{R}\right) . \tag{45}$$

where

$$R_s \equiv \frac{2GM}{c^2} \tag{46}$$

is the Schwarzschild radius corresponding to the total mass M. We see from Eq. (45) that if there is sufficient turbulence (in the sense that the maximum gas velocity is high enough compared to the Alfvén speed), the object can be stabilized against the relativistic instability which has posed a problem in other models of quasars.

F. Let us now inquire into the possibility that the model that has been developed in the previous section is applicable to understanding the observed properties of quasar nuclei. For this purpose we shall take the object 3C 273B as a particular example. Since it is the closest known quasar to our Galaxy, more extensive and detailed observational data currently exist for this object than for any other of its type.

We begin by considering the implications of Eq. (45) determining the frequency of radial pulsations. New evidence for a 13-year periodicity in the variations of the optical continuum of 3C 273B has recently been found by W. Kunkel and H. J. Smith:[14] four harmonics of a fundamental mode corresponding to a 13-year period show up when the optical data is frequently analyzed. Adopting the corresponding value of ω, $10^{8.2}$ $\sec^{-1}$, we find that Eq. (45) approximates the form

$$10^{8} A^{2} M R^{-3} - 10^{-20} M^{2} R^{-4} = 1 \; . \tag{47}$$

Curves which express this relation between M and R are shown in Fig. 4, for three values of the Alfvén number A.

The lower branch of each curve, which is shown in broken lines, is of little interest, for in this region the two terms in the parentheses of Eq. (45) are almost equal, so that comparatively small changes in the parameters could make the object unstable.

Since the red-shift of the spectral lines of 3C 273 is $z = 0.158$, and we are following Greenstein and Schmidt[15] in interpreting this as a cosmological red-shift, it is necessary that R_s/R should be much less than z. We somewhat arbitrarily require that $R_s/R \leq 10^{-2}$, and this implies that the parameters of the nucleus should be represented by a point above and to the left of the line marked "RED-SHIFT LIMIT" in Fig. 4. It is worth noting, for later reference, that these considerations lead to an

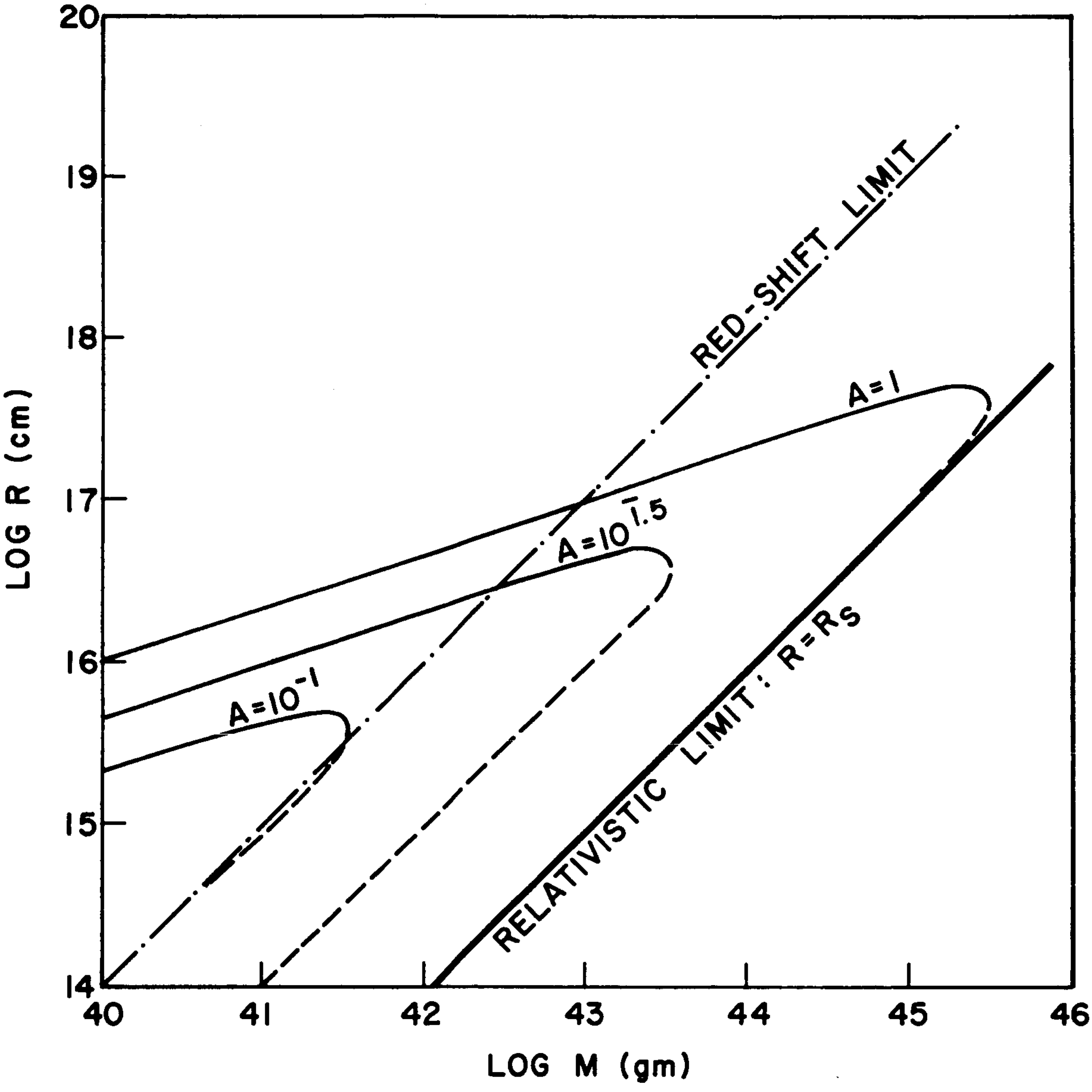

FIG. 4. MASS-RADIUS DIAGRAM FOR OBJECT WITH RADIAL OSCILLATION PERIOD OF 13 YEARS.

upper limit on the mass of 10^{43} gm. However, this limit corresponds to $A = 1$, which is physically unacceptable since, among other reasons, the gas velocity would be comparable with the escape velocity. (The escape velocity is comparable with the Alfvén velocity.)

If the turbulence velocity is to be, say, 10^{-1} times the escape velocity, we must have $A = 10^{-1}$. One choice of parameters is then the following:

$$A = 10^{-1}, \quad R = 10^{15.7} \text{ cm}, \quad M = 10^{41.3} \text{ gm} = 10^{8} M_{\odot} ,$$

which leads to the following values for related parameters:

$$v_A = 10^{9.2} \text{ cm sec}^{-1}, \quad v_{max} = 10^{8.2} \text{ cm sec}^{-1}, \quad B = 10^{6.5} \text{ gauss} .$$

The above value for the turbulence velocity is comparable with, and somewhat smaller than, the velocities inferred by Greenstein and Schmidt[15] from linewidths, on the assumption that lines are broadened by the doppler effect. We find from Eq. (30) that the gravitational binding energy is $10^{59.5}$ erg. The magnetic energy has the same value. Hence if some fraction of the magnetic energy can be converted into high-energy electrons, it will be possible to meet the energy requirements of strong radio sources.

We may also note that the radius is only about one light-day, so that there is no difficulty in understanding light flashes with durations of about one month.

G. In Section B it was concluded that the magnetic field configuration associated with quasi-stellar objects must be open, of primeval origin, and coupled to the nucleus, but we have yet to investigate the specific structure of this field. First, consider the schematic model of a galaxoid and its associated field as illustrated below in Fig. 5. The presence of the magnetic field will drastically affect the accretion process since highly conducting gas can flow only along the lines of force. An "open" pattern of the sort illustrated in Fig. 5 provides a mechanism for funneling intergalactic gas into the galaxoid. The resulting influx of matter and energy might even be substantial enough to ease the problem of explaining

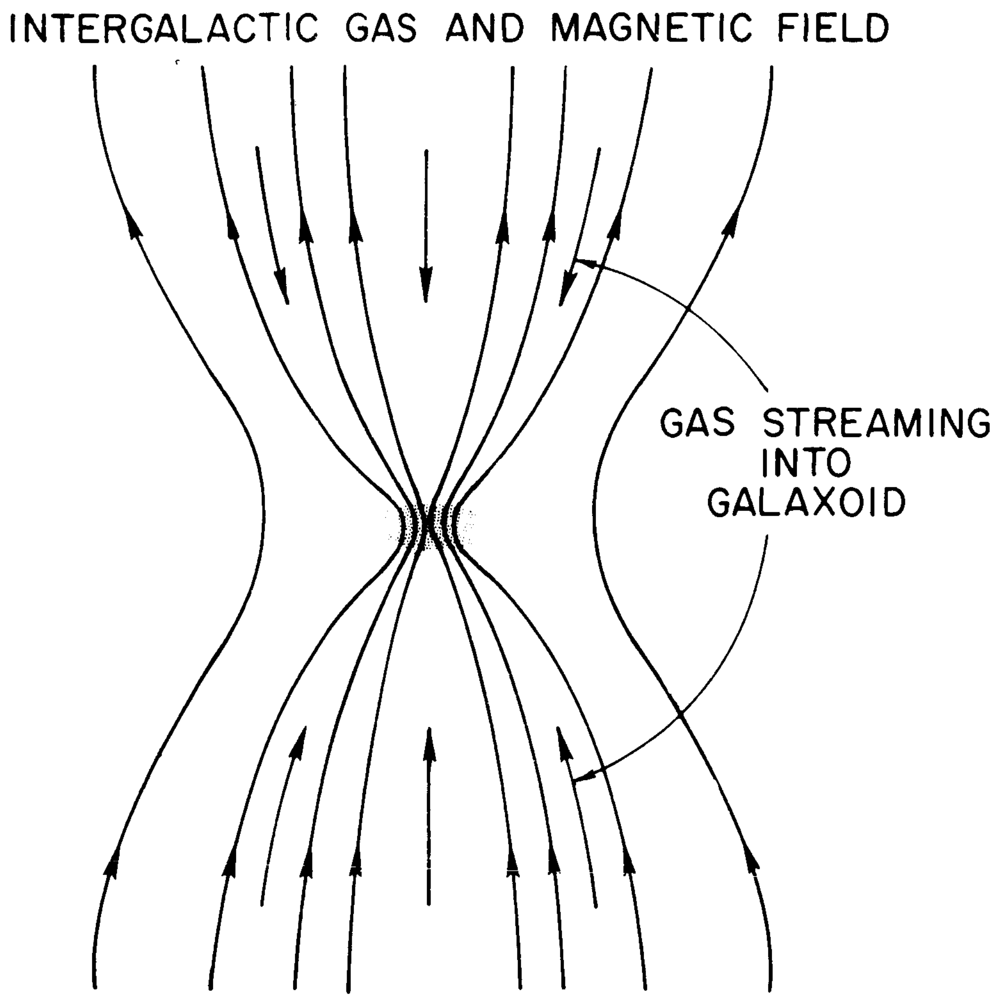

FIG. 5. SCHEMATIC MODEL OF GALAXOID.

the great luminosity of 3C 273 and to reduce the time scale for the whole quasar phenomenon.

In seeking the proper kind of transition between the magnetic fields that are coupled to the quasar nucleus and those that are not, we have been led to a structure with a sheet pinch and an accompanying Y-type neutral point (a Y-type neutral line, in three dimensions) - analogous to the model that has previously been employed to explain the high-energy phase of solar flares.[16]

It seems that it is impossible to find a completely force-free field configuration; the field outside the nucleus must have "singularities" of the type represented by neutral sheets and neutral lines. This fact has the immediate consequence that the flare mechanism[16] can be operative, so that we now see the prospect of understanding the similarity between solar flares and the high-energy phenomena of quasi-stellar objects and radio galaxies.

The important point about this configuration is that <u>it possesses magnetic energy in a form that is available for release by a plasma instability</u>. If the field had, say, a current-free dipole configuration, there would be no way to release magnetic energy since the field would already be in its lowest energy state (assuming fixed boundary conditions at the surface of the galaxoid).

If we assume that the galaxoid and associated magnetic field pattern have rotational symmetry about an axis parallel to the distant magnetic field, there must be singularities in the magnetic field on the "equatorial plane." One of the simpler field configurations is shown in Fig. 6: the magnetic field outside the galaxoid contains a disk-type sheet pinch bounded by a circular Y-type neutral line. This neutral line separates two sets of magnetic field lines: those which thread the galaxoid and those which do not. Since the high-energy phase of solar flares was ascribed to developments at a neutral sheet located in a coronal streamer, we may anticipate that similar developments at the neutral sheet of the present quasar model will lead to a "galactic flare." If one follows the same line of argument which was used to explain the high-energy phase of a solar flare, we are led to a galactic-flare development as indicated in Fig. 7.

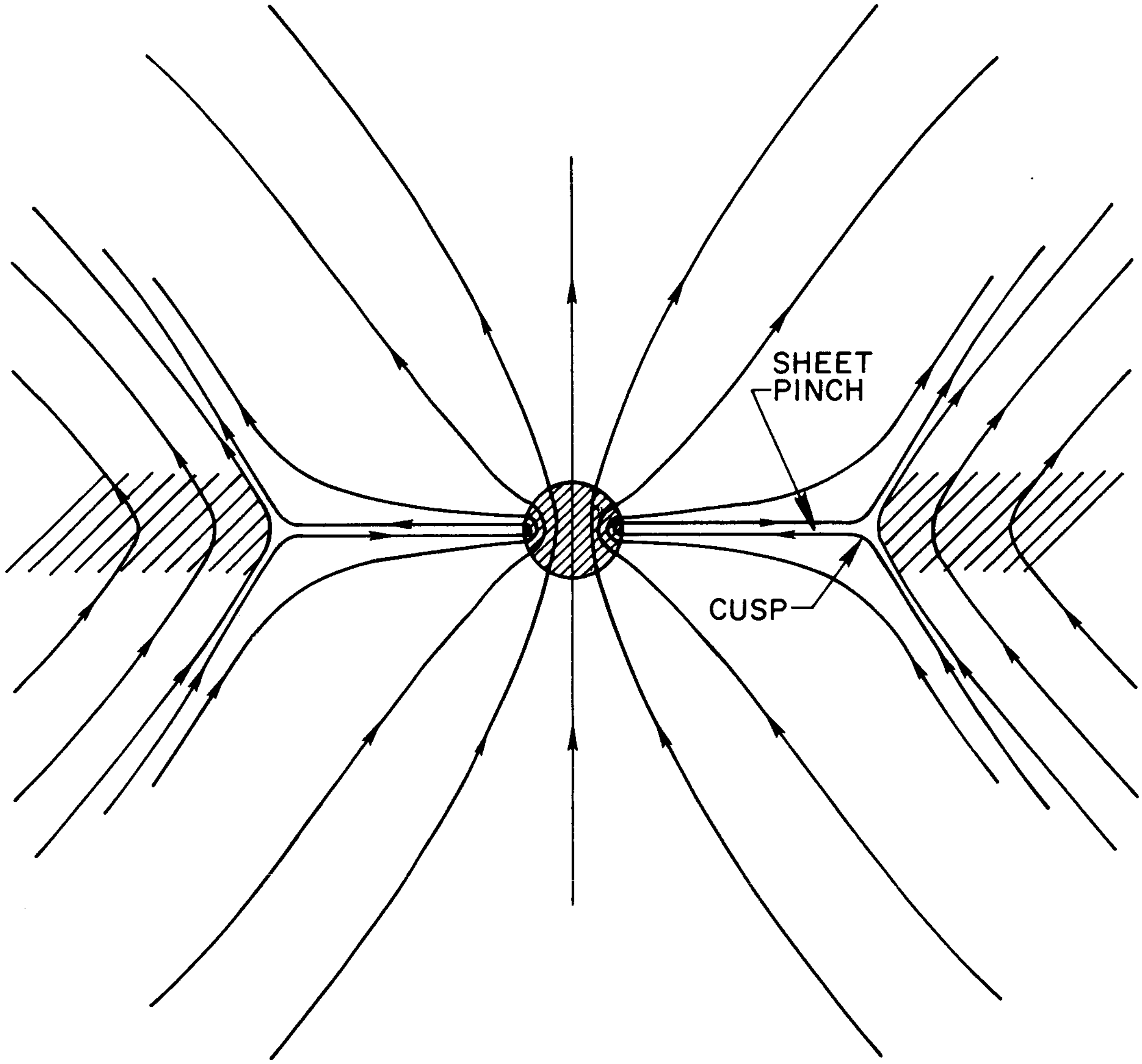

FIG. 6. POSSIBLE FIELD CONFIGURATION WITH AXIAL AND REFLECTION SYMMETRY.

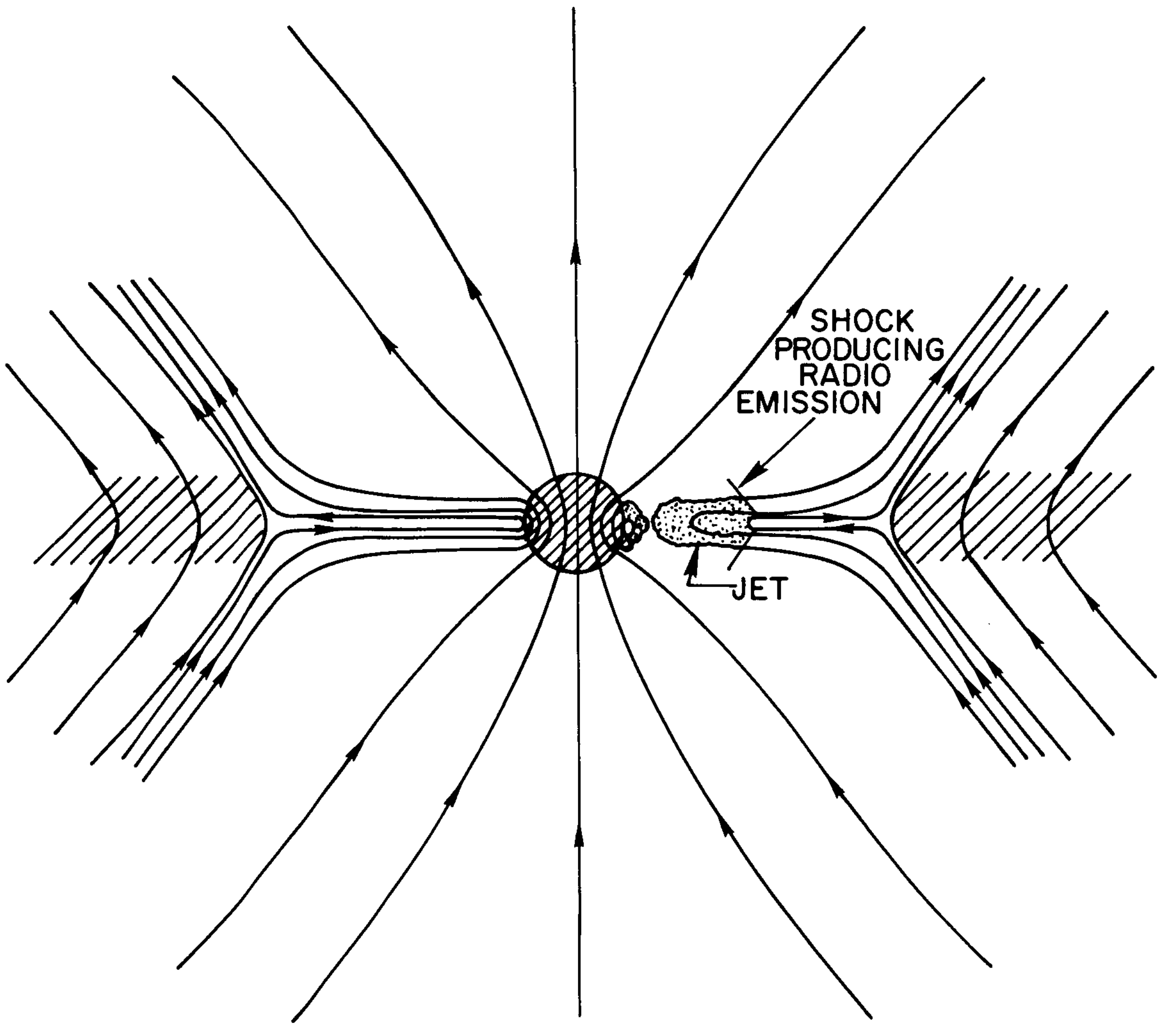

FIG. 7. EFFECT OF FLARE MECHANISM ON MAGNETIC FIELD.

Any plasma instability such as the tearing-mode instability that can occur along the neutral sheet will lead to a rearrangement of the magnetic field pattern. Specifically, the field that is coupled to the nucleus is likely to become closed and attain a lower-energy, dipole-like configuration. Thus, this mechanism would provide a way to decouple a galactic or proto-galactic magnetic field from the general intergalactic field. Some of the electrons and protons which are accelerated during the instability will "hook on" to the newly closed field lines connected to the galaxoid. Some of these particles may remain trapped, by magnetic mirror action, for some time and so form "radiation belts." These particles will radiate by the synchrotron mechanism and this may explain the small-diameter radio emission from quasars. In view of the very high magnetic field strengths contemplated, proton synchrotron radiation will be important, as well as electron synchrotron radiation. Furthermore, the radiation may extend beyond the radio spectrum into the infra-red and optical parts of the spectrum. Any particles with pitch angles inside the "loss cone" of the magnetic mirror will impinge upon the surface of the galaxoid. As in the case of solar flares,[17] this process would yield impulsive x-ray emission. There are many important questions to consider in connection with this part of the flare process, but there is no time to discuss them here. We merely note that the flare process offers a simple explanation for impulsive "flashes" at the galaxoid in the radio, optical and possibly also in the x-ray bands. We now turn our attention to that part of the flare associated with the field lines which remain "open" after reconnection.

The field that is detached from the quasar nucleus by the tearing-mode instability must still remain coupled to the general intergalactic magnetic field. A "bag" of turbulent magnetic field containing plasma and high-energy particles will then be ejected by the tension of this detached field. As a result, a shock wave will form at the leading edge of the ejected "bag" of plasma; and if the instability has accelerated a significant number of the charged particles in the "bag" to relativistic energies, this shock front will advance at nearly the speed of light.

If the instability occurs locally in only a small portion of the field pattern (a small range of "longitude"), the result will be a jet moving outward from the galaxoid. This is illustrated in Fig. 7. We now propose that the jet of 3C 273 (component A) and the jet of the galaxy M 87 were formed in just this fashion. The mechanism also provides for the possibility of a sequence of such instabilities and jets, as recent observations indicate are likely. There is, moreover, an additional source of particle acceleration at the shock front at the tip of the jet. Electrons which are accelerated at the shock front will lose energy by synchrotron radiation on leaving the shock front, so that the radio emission which they produce is likely to be centered on the tip of the jet. Moreover, localized injection followed by extended synchrotron radiation will produce a particle energy spectrum with index close to -2, so that the radio spectrum will have an index close to -0.5. It is possible, therefore, that the radio source 3C 273A, which is localized at the tip of the jet and has a spectral index[18] of about -0.7, is to be associated with a shock front at the tip of the jet.

It is remarkable that the jet itself is visible optically, having the featureless bluish continuum spectrum characteristic of synchrotron radiation, but does not show up at radio frequencies. This implies that the radiation spectrum and electron spectrum are less steep than those associated with 3C 273A. This means that acceleration must be in progress in the jet.

This hypothesis enables us to estimate the strength of the field at the tip of the jet. The optical luminosity of the jet is about $10^{44.3}$ erg sec^{-1}. A conservative estimate of the field strength at the tip of the jet can then be made by assuming that the shock front at the tip is relativistic, advancing at nearly the speed of light. That is, we equate the observed rate of optical radiation to the rate of destruction of magnetic energy:

$$\frac{1}{8\pi} B_{tip}^{2} \, A \, c = 10^{44.3} \text{ erg sec}^{-1} \, . \tag{48}$$

Taking A, the cross-sectional area of the jet,[15] to be approximately $10^{43.9}$ cm^2, we find $B_{tip} = 10^{5.6}$ gauss.

This raises some interesting questions. The field coupled to the galaxoid was force-free (except at the neutral sheet) before the onset of the instability that produced the jet. If the jet is narrow (as in 3C 273), the instability must have occurred over a small range of galaxoid longitudes. Hence, the greater portion of the magnetic field pattern in both hemispheres would be left unchanged (and still force-free). Thus, the total magnetic flux associated with the galaxoid can be estimated from the field strength at the tip of the jet and the distance of this tip from the nucleus, i.e.,

$$\Phi = 2\pi R_{tip}^{2} B_{tip} . \tag{49}$$

For 3C 273A, R_{tip} is at least $10^{23.2}$ cm, and B_{tip} is $10^{\bar{5}.6}$ gauss from Eq. (48). Therefore, the magnetic flux through each hemisphere of this quasar amounts to some $10^{42.8}$ gauss cm^2. Referring to the relation between magnetic flux and mass given by Eq. (33), we find that this flux must be associated with a mass of $10^{45.8}$ gm = $10^{12.5}$ $M_{\odot}$.

It could be, of course, that the optical luminosity of the jet is not derived from magnetic field annihilation alone; certainly, some of the energy of the jet must be stored in the form of high-energy particles, including protons. Our estimate should probably be interpreted as an upper limit to the central mass. However, the mass derived by this argument is much bigger than 10^8 $M_{\odot}$, the value obtained in Section F. On noting that the Schwarzschild radius of an object of mass $10^{12.5}$ $M_{\odot}$ is about one light-year, we see that it is impossible to fit so much mass into an object compact enough to display light fluctuations of about one month time-scale.

It is possible to resolve this dilemma if we are willing to accept the hypothesis that the visible object 3C 273 is surrounded by a much larger mass of gas which is "invisible," presumably because it is fully-ionized and of low density. If this ionized gas extends as much as several kiloparsecs out from the quasar, it would not be expected to affect the optical or radio emission in a detectable way. This hypothesis also enables us to fit quasi-stellar objects into an evolutionary scheme with ordinary galaxies. A mass of about 10^8 $M_{\odot}$ may make it possible to picture a quasar as an object which will evolve into a galactic nucleus, but the nucleus is part of a galaxy, so that it is necessary to understand the evolution of the rest of the galaxy also. If a quasar is typically surrounded by a much larger mass of gas, one has the necessary ingredients for the main body of a galaxy as well as its nucleus.

This ionized gas will also be a source of x-ray bremsstrahlung radiation. As much as 10^{46} erg sec^{-1} of x-ray emission can be produced by fully-ionized hydrogen gas at a temperature of 10^{6} °K if the gas extends to a distance that is less than 5 kpc from the quasar nucleus. This result depends only weakly on the temperature. Now we can perhaps hope to understand the recent observations of Byram, Chubb and Friedman[19] that certain radio galaxies emit energy in the form of x-rays at a rate that exceeds the combined optical and radio flux by one or two orders of magnitude, if we can relate radio galaxies with quasars.

H. We have yet to consider the question of how ultra-relativistic particles (e.g., 10^{12} - 10^{13} eV electrons) are produced in quasars and radio galaxies. In our opinion this problem is fully as important as the origin of the very large optical luminosities of quasars. Unfortunately, very little attention has been given to understanding how great acceleration of charged particles can occur. Nuclear processes are unlikely to meet the requirements. Even if a significant amount of the rest mass of quasi-stellar objects is converted to energy and divided up among the constituent particles, only a few MeV per particle, at the very most, can be expected. Almost from the outset we are forced to conclude that <u>if high-energy particles exist in nature, it must be the result of electric fields</u>. However, there are difficulties in applying this simple hypothesis to quasars. First, <u>the acceleration must occur in a low-density medium</u> so that the effects of collisions are negligible. More important, since we are dealing with a high-conductivity plasma where uniform fields cannot exist, <u>the required process must be one of stochastic acceleration</u>,[20] most likely by the turbulent electric fields which result from plasma instabilities. For the case of solar flares this has been known and appreciated for some time; however, it is only recently that this has begun to be realized <u>vis à vis</u> the particle acceleration in quasars and radio galaxies.

Can stochastic acceleration in quasars produce electrons with energies as high as $10^{12.3}$ eV (necessary for the emission of optical synchrotron radiation in a magnetic field of $10^{5.6}$ gauss)? If the instability is a nonlinear one like the tearing-mode instability,[21] it will result in a very large number of small filaments. Let us estimate the average electric field strength in the filaments. This is given by

$$\langle E \rangle \sim \frac{v_A}{c} \langle B \rangle \tag{50}$$

where $\langle B \rangle$ is the average magnetic field in the filaments. Therefore, an absolute upper limit to the electron energy is given by

$$eW_{max}(\text{esu}) \sim e\langle E \rangle c\tau_{jet} \sim e\langle B \rangle v_A \tau_{jet} \sim e\langle B \rangle L,$$

where τ_{jet} is the lifetime of the jet and L is the length of the jet. Since $\langle B \rangle \lesssim 10^{5.6}$ gauss and $L \sim 10^{23}$ cm for the jet of 3C 273, we find that

$$W_{max} \sim 10^{18.6} \text{esu} = 10^{21.1} \text{eV} .$$

This is considerably higher than is needed, so the comparatively inefficient process of stochastic acceleration may be operative in this case. Let us first estimate how many "steps" are involved. Suppose that the scale over which the field is uniform is comparable with the gyro-radius of a 10^{12} eV electron in a field of $10^{5.6}$ gauss, i.e., $\lambda \sim 10^{15.5}$ cm. Then, the time for a high-energy electron to traverse the length λ is approximately $\lambda/c \sim 10^5$ sec. The lifetime of the jet is some 10^5 years $\sim 10^{12.5}$ sec. Therefore, the number of "steps" of length λ in this time is $N = 10^{7.5}$. The average energy of an ensemble of particles subjected to a stochastic acceleration of N steps of energy $e\langle E \rangle \lambda$ each is just

$$\langle W \rangle \sim N^{1/2} e\langle E \rangle \lambda \sim N^{1/2} e\langle B \rangle \lambda .$$

Numerically, this is

$$\langle W \rangle \sim 10^{14.9} e \text{ esu} = 10^{17.4} \text{ eV} .$$

Hence, even a stochastic process is capable of providing more than enough acceleration. A proper calculation of the electron energies would have to take account of the synchrotron losses, which get higher with increasing particle energy. The interaction between stochastic acceleration and the synchrotron loss mechanism is very complex and will not be considered here.

Protons are subject to exactly the same stochastic acceleration as electrons, but they are virtually unaffected by the synchrotron loss mechanism due to their greater mass. The jet in 3C 273 must contain $10^{12.3}$ eV electrons in order to produce optical synchrotron radiation where the field is only $10^{\bar{5}.6}$ gauss. These electrons lose $10^{1.3}$ eV sec^{-1} by the synchrotron mechanism. Therefore, the maximum acceleration rate must be at least this amount. Those protrons which have been subjected to this maximum rate of stochastic acceleration for the entire lifetime of the jet ($\geq 10^5$ yrs $\sim 10^{12.5}$ sec since its length is $\sim 10^{23}$ cm), will have achieved energies in excess of $10^{13.8}$ eV. Multiply-charged ions will have reached even greater energies. Hence, it is possible that galactic flares are responsible for at least a portion of the high-energy component of cosmic rays.

I. Let us now consider the likely evolution of the jet of 3C 273 on the basis of our model. It will continue as a jet until it reaches the ring-shaped neutral line. At this point the supply of magnetic energy will cease, and there will be no further acceleration. The jet will then divide into two plasma clouds, as illustrated in Figure 8. (Note that it is the momentum of the protons that determines whether the jet breaks up or continues to stream as a jet through the weakening magnetic field.) Hence, a single galactic explosion eventually results in two quite similar radio clouds at roughly equal distances from the nucleus. If instead of being localized, a galactic flare were to involve the whole sheet pinch at once, the final result would be two "smoke ring" radio clouds diametrically opposite with respect to the quasar nucleus. Thus our model seems to offer a simple explanation for one of the most striking characteristics of radio galaxies: their double structure.

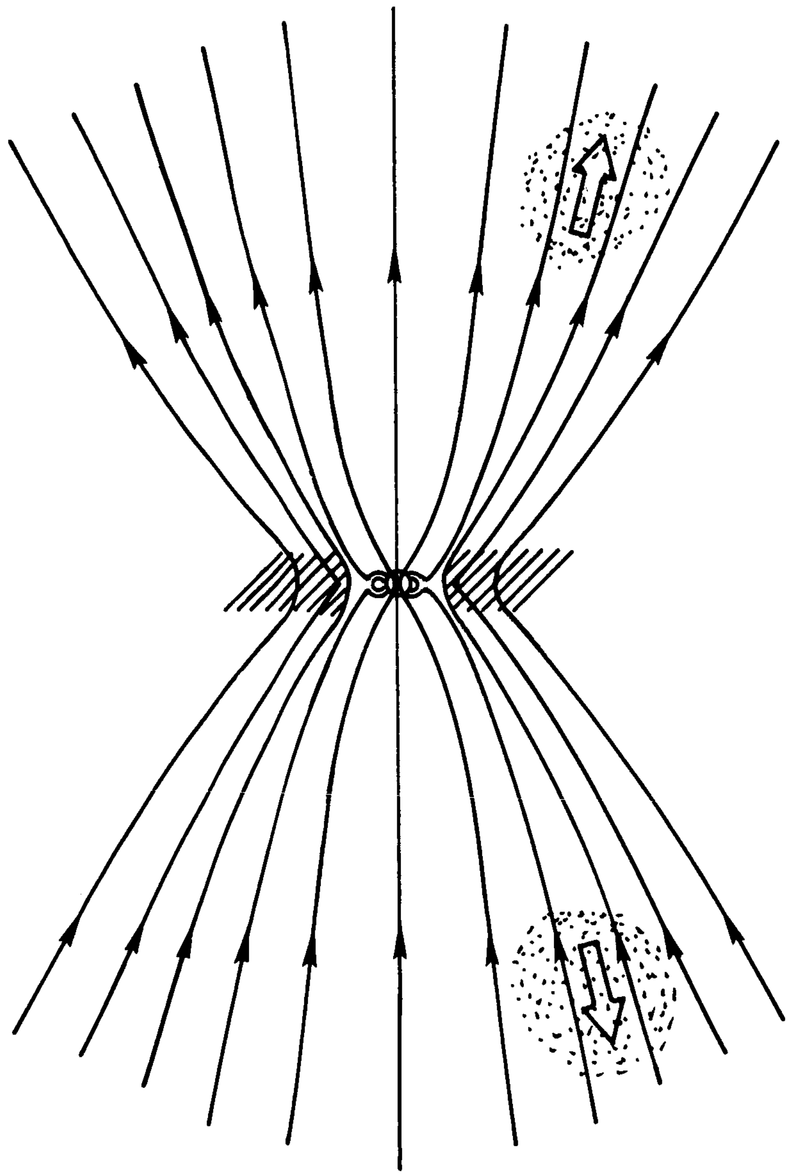

FIG. 8. EVOLUTION OF DOUBLE RADIO SOURCE
FROM SINGLE FLARE.

J. We now consider requirements on the intergalactic gas and the intergalactic magnetic field.

We have seen that the intergalactic magnetic field is an important ingredient in our model for determining how a quasar will develop. Chandrasekhar[22] noted that a uniform field will not inhibit the gravitational condensation of a mass of gas if the mass is sufficiently large, even if the magnetic pressure is comparable with the gas pressure; however, the field will certainly affect the way in which the object condenses. Also, since the "open" intergalactic magnetic field couples the quasar nucleus with intergalactic space, it is possible to understand why the formation of a small, very massive object would not have to be inhibited by the accretion of angular momentum. Namely, the "open" field configuration provides a mechanism for retaining a low angular velocity during condensation by transferring angular momentum from the inner regions to the outer regions. There is a limit to this process after which point no more angular momentum can be thrown off; this process will cease when the gas density is so high that

$$v_A < v_{st}$$

where v_{st} is the streaming velocity of accreting gas. It is possible that this mechanism for retaining low angular velocity operates in the quasi-stellar stage of galactic evolution; but when it ceases, the object begins to grow in dimension and a galaxy, which would probably be a radio galaxy, is formed.

There is no great problem in understanding the luminosity of quasars if the energy influx of intergalactic gas is taken into account. For example, the case of 3C 273 where the radiative flux is 10^{46} erg sec^{-1} can be explained if the accretion rate due to gas influx is as low as $10^{27.2}$ gm sec^{-1} = $10^{1.4}$ $M_{\odot}$ yr^{-1}. This gives an evolution time (the time for the nucleus to double its mass) of less than $10^{7.5}$ yr, which is quite rapid on a galactic time scale.

We can now estimate the strength of the intergalactic magnetic field. The density of intergalactic matter ρ_o is believed to be about 10^{-28} gm cm^{-3}. Hence the radius R_c of the sphere from which the quasar 3C 273 and its surrounding gas have condensed is about $10^{24.4}$ cm or 800 kpc. The Jean's criterion is admittedly open to criticism,[23] but we may use it to estimate the temperature of intergalactic gas which would lead to the formation of an object of this mass. The Jean's criterion leads to

$$R_c = a_o (42G\rho_o)^{-1/2} \tag{51}$$

where a_o is the speed of sound. With the above values for R_c and ρ_o, we find that $a_o = 10^{7.3}$ cm sec^{-1} so that the temperature of the intergalactic medium is about $10^{6.3}$ °K. This may seem high, but it has recently been shown that the density of neutral hydrogen in intergalactic space is exceedingly low.[24]

In the case of 3C 273, we estimated that the total magnetic flux is $10^{42.8}$ gauss cm^2. Since this flux once threaded a sphere of radius R_c, the primeval magnetic field must have had an intensity of $10^{\overline{7}.5}$ gauss. It appears that the primeval magnetic pressure was comparable with the intergalactic gas pressure, but no great significance should be attached to this result, since it depends sensitively on the density and temperature of the intergalactic gas which are quite uncertain.

K. The preceding model is being proposed partly as a plausible interpretation of quasars, and partly as a basis for further theoretical investigations. We now make some final comments on some of the implications of this model, indicating further aspects needing calculation.

Although these lectures have concentrated on quasars and their explosions, giving rise to radio clouds and other phenomena, we should note that there is no reason why the model should not apply, with only minor modifications, to radio galaxies also. It has been suggested that a quasar may in fact be an early stage in the evolution of a galaxy, implying that the magnetic field of a galaxy may have a structure similar to that which was described as a "galaxoid." The principal changes are probably (1) the mechanism for getting rid of angular momentum may have ceased to operate, with the consequence that angular momentum limits the contraction, so that the resulting galactic nucleus is much larger than the earlier quasars; and (2) some flares may have occurred, resulting in some decoupling of the galactic magnetic field from the intergalactic magnetic field.

If one assumes that the magnetic field of quasars and galaxies is derived from a primeval magnetic field (and one really faces formidable theoretical difficulties if one does not make this assumption), then the problem of understanding the evolution of galaxies involves, as an important sub-problem, that of understanding the change in structure of the magnetic field, including changes which lead to reconnection of the magnetic field. It seems from our knowledge of plasma physics that the principal mechanism for reconnection will be the tearing-mode instability.[21] From the picture we have given of solar flares,[16] it then follows that the phenomenon which leads to reconnection of galactic magnetic fields is that of galactic flares.

We know that a center of activity on the sun exhibits continual activity, not simply occasional major flares. Much of this activity can be understood as the continual occurrence of micro-flares--small-scale instabilities giving rise to minor changes in the magnetic-field pattern, and releasing small amounts of energy. If our model of quasars is correct, we should expect that the same will be true of quasars, so that we have a simple way of understanding the continual "noise" which is manifested as rapid fluctuations in optical and radio output. It should be noted that there must be some continuous form of non-catastrophic instability (which may involve some mechanisms of MHD instability) in order to provide a continuous supply of energy in the form of MHD turbulence, which appears to be necessary in order to maintain gross stability. It could be that the object has a peculiar kind of metastability, in the sense that a certain level of non-catastrophic instability is necessary to suppress a catastrophic instability. One of the significant points about the flare instability is that the energy released by the flare can be a large fraction of the stored magnetic energy, which can be much larger than the binding energy (the energy determining the oscillation frequency); this means that a flare must give rise to a drastic change (some kind of collapse) in the configuration of the quasar, but the nature of this change has not been studied.

This occurrence of low-level activity is important also in trying to understand periodic phenomena, such as the oscillations of 3C 273. It is not enough to have a mode of oscillation; we must also have impulsive disturbances which can excite these oscillations. Flares will provide such excitation if they lead to sufficiently strong dynamical impulses on the quasar.

On bearing in mind that our model involves an approximate balance between magnetic and gravitational forces, one can readily appreciate that, since a flare produces a sudden change in magnetic connection, it will also produce a sudden change in the forces to which a quasar is subject. If the forces are symmetrically distributed around the "equator" of the quasar, the principal result would be the excitation of radial oscillations. However, if the flare is asymmetrical, involving more decoupling on one side of the quasar than on the other, the quasar will then be exposed to an unbalanced force, which will produce acceleration in the direction opposite to that in which the decoupling has occurred.

One might suppose that an object as massive as a galaxy could hardly experience any significant acceleration, but this is not so. As a simple though extreme example, suppose that a flare were to decouple the magnetic field from one hemisphere ("East" or "West") of the "nucleus" of 3C 273. Then the magnetic field which remains connected both to the nucleus and intergalactic space will exert a force of order

$$F \approx 2\pi R^2 \frac{1}{8\pi} B^2$$

which amounts to $10^{43.8}$ dyne. Since the mass is $10^{41.3}$ gm, the resulting acceleration is $10^{2.5}$ cm sec^{-2}. In order to appreciate the magnitude of this acceleration, we may note that it would lead to acceleration to a relativistic speed in only 10^8 sec, i.e., 3 years!

The problem rapidly becomes complicated, however, since the magnetic field must readjust in response to the movement of the quasar. The force exerted by the magnetic field will probably not change greatly from its initial value until the displacement of the quasar is comparable with its radius. Hence a more meaningful set of numbers is provided by the estimate that the quasar will move a distance equal to its radius in $10^{6.7}$ sec, i.e., 50 days, and that by this time it will have accelerated to a speed of $10^{9.2}$ cm sec^{-1}, i.e., a speed of order 10,000 km sec^{-1}.

One may obtain another estimate of the maximum velocity which the quasar could acquire by noting that it cannot exceed the speed at which the magnetic field can readjust to the changes in boundary conditions, which is given by the Alfvén velocity. The Alfvén velocity in the interior of the model of the quasar 3C 273 is $10^{9.2}$ cm sec^{-1}, but it should be noted that it should be higher than this immediately outside the quasar, since the density should drop off sharply whereas the strength of the magnetic field will not.

Our model therefore provides for the possibility that a quasar (or a galaxy, for that matter) could acquire a high velocity in a short time. This may help one to understand that absorption-line measurements indicate that at least four quasars are moving with a speed of order 10^8 cm sec^{-1} with respect to the neutral gas surrounding them.[25,26,27,28] This possibility is also compatible with the view of Ambartsumian[29] that groups of galaxies sometimes have positive total energy, implying that the group is dispersing, and that when a pair of galaxies are associated with strong radio emission (such as Cygnus A), they may in fact be moving away from each other. This possibility also offers the prospect of understanding the remarkable associations of galaxies and radio sources which has been discovered and described by Arp,[30] although in our view it remains very difficult to accept as real the association of a galaxy with a small red-shift and a quasar with a large red-shift. However, these associations represent only a small fraction of the associations noted by Arp, and this small fraction may prove to be chance coincidences.

The possibility that a quasar may, as a result of a galactic flare, have acquired a high velocity relative to the surrounding intergalactic gas has the important implication that the magnetic field may have a pattern which differs in an important way from that depicted in Figure 6. If a quasar is moving at high speed relative to the surrounding plasma, the magnetic field of the quasar will be deformed in a manner somewhat like the deformation of the earth's magnetic field by the solar wind.[31] Namely, the bipolar magnetic field of the quasar would be deformed into a long bipolar flux tube, similar to the "double-barreled" tail of the magnetosphere,[32] and to the model which we have proposed for the magnetic field of a coronal streamer.[16]

If we consider that the magnetic field of the quasar 3C 273 may be of this form, we can immediately obtain more satisfactory answers to two of the questions which arise in our discussion of this object. First, we can understand why the flare occurs only over a narrow range of angles, appearing as a "jet," rather than over a complete ring. The flare would be confined to the comet-like tail of the quasar, which guarantees a jet-like appearance. Second, there is no longer a serious discrepancy between the estimate of the magnetic flux obtained from our analysis of the oscillation frequency of the nucleus of the quasar and the estimate of the flux derived from our calculation of the magnetic-field strength in the jet. If the entire flux from the nucleus in fact passes through the visible jet, then the field strength at the tip of the jet would be $10^{\bar{6}.2}$ gauss. There is still a discrepancy between this figure and the estimate of $10^{\bar{5}.6}$ gauss based on the energetics of the jet, but the discrepancy is now small enough that it could be resolved by choosing different parameters for the nucleus, e.g., $A = 10^{\bar{1}.5}$, $M = 10^{42.5}$ gm and $R = 10^{16.4}$ cm.

In order to understand and attempt to calculate the explosions of quasars and galaxies which give rise to radio emission, it is necessary to form a model of the magnetic and plasma structure of the object. This structure must satisfy certain requirements in order to provide for the stability (or meta-stability) of the object, and for the possibility of a plasma instability which can lead to particle acceleration and subsequent radio emission. However, we have also seen that these instabilities may have dynamical consequences which are strong enough to induce turbulence (which has a macroscopically stabilizing influence), radial oscillations, and also directed motion with respect to the surrounding intergalactic medium. The tearing-mode instability also has the important consequence of magnetically detaching the object from the intergalactic medium. Galactic flares therefore have significance over and above their importance in producing radio (and sometimes optical) emission: it appears that a full understanding of the evolution and structure of quasars and galaxies will depend upon a detailed understanding of galactic flares.

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